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A Comprehensive Comparison of Floating and Ground-Mounted Photovoltaic Systems: A Review

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Abstract: - As global energy demand rises and climate change concerns intensify, there is a growing need for innovative energy solutions. Solar Photovoltaic (PV) systems have emerged as a sustainable option, but land availability and environmental impacts remain significant challenges. Floating Solar PV (FPV) systems offer a promising alternative, particularly in regions with limited land resources. This study aims to compare Floating PV systems with traditional ground-mounted PV systems, assessing their efficiency, energy potential, and the advantages of overcoming the limitations of ground-based installations. The objective is to determine how FPV systems can address the growing demand for renewable energy while minimizing environmental impact. The research involves an in-depth review of recent global case studies, industry reports, and academic research on Floating PV systems. Comparative analyses focus on factors like land use, environmental impact, and energy efficiency to evaluate the viability and future of FPV systems. The review reveals that Floating PV systems offer distinct advantages, such as the utilization of water bodies to avoid land use conflicts and a reduction in environmental impact. These systems show promise in improving energy efficiency by maintaining lower operating temperatures compared to ground-mounted systems. Furthermore, the potential for scaling FPV in untapped markets is significant. Floating PV systems present a transformative solution for meeting rising energy demands while addressing land scarcity and environmental concerns. This study highlights the critical role of FPV in the future of renewable energy adoption and provides valuable insights for decision-makers in the energy sector.

Keywords: Floating Solar PV, Ground-Mounted PV, Renewable Energy, Floating Photovoltaic Systems.

I. INTRODUCTION

The world's expanding population and increasing energy demands have led to a substantial rise in fossil fuel consumption, intensifying greenhouse gas emissions and contributing to global climate change. Renewable energy sources—such as hydro, solar, wind, and bioenergy—offer sustainable, cost-effective, and environmentally friendly alternatives to traditional energy production. According to the International Energy Agency (IEA), renewables account for 29% of the global electricity supply, emphasizing their role in achieving energy sustainability[1]. Among these, solar energy has emerged as a leading option due to its abundance and negligible greenhouse gas emissions. Its benefits include diversification of energy resources, reduced reliance on fossil fuels, rural electrification, and minimized environmental impact[2]. However, significant challenges, including land requirements and limitations in research and manufacturing, restrict its scalability. For instance, installing a 1 MW photovoltaic (PV) plant typically requires 2.3 acres of land. Moreover, achieving global net-zero emissions by 2050 necessitates a 25% annual increase in solar energy generation, as emphasized by the IEA [3]. Floating solar photovoltaic (PV) systems present a viable solution to land constraints, leveraging water bodies to host solar arrays. These systems not only address land scarcity but also reduce water evaporation and enhance energy efficiency through the cooling effect of water. Successful implementations of floating solar PV in countries like India and Brazil highlight their potential[4][5]. However, challenges such as occupational hazards, ecological impacts, and weather-induced risks must be addressed to promote widespread adoption [6].

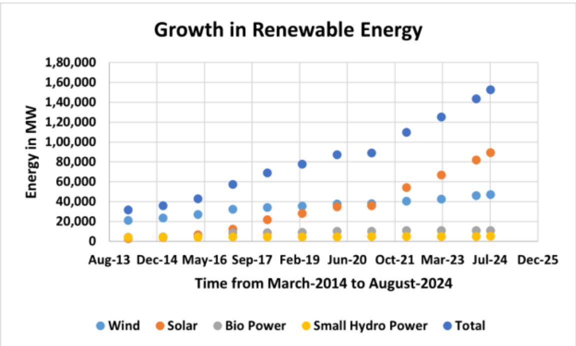

Figure 1: Growth in Renewable Energy in India till August 2024.

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Research indicates that floating solar PV systems can produce higher energy output than ground-mounted systems due to water-based cooling effects[7]. Furthermore, floating installations reduce deforestation and habitat destruction associated with land-based PV plants[8]. Studies from regions with high solar irradiance, such as India and Brazil, underscore the feasibility of this approach[9[10]. While floating solar PV projects have demonstrated success, significant challenges remain that must be addressed to enhance efficiency and encourage broader adoption. This paper focuses on two primary objectives:

1. Evaluating the benefits and drawbacks of floating PV systems compared to land-based systems, particularly regarding energy output and environmental impact.
2. Identifying and analyzing the challenges facing the floating solar market, especially those related to scalability, including technological, economic, and environmental barriers.
3. The research aims to provide actionable insights for optimizing floating PV technology and supporting its integration into mainstream renewable energy strategies.

The study focuses on comparing floating and ground-mounted PV systems concerning efficiency, land use, environmental impact, and operational challenges. It excludes other renewable energy sources to maintain a targeted analysis. While the study highlights global trends, specific emphasis is placed on India due to its substantial solar energy adoption[11].

Paper Organization

Introduction: Provides context, defines the research objectives, and outlines the scope of the study.

Literature Review: Summarizes previous studies, identifies research gaps, and establishes the need for this comparative analysis.

Materials and Methods: Describes the methodology, data sources, and analytical framework used in the study.

Results and Discussion: Presents findings comparing floating and ground-mounted PV systems, discussing their implications relative to existing literature.

Conclusion: Summarizes the contributions of the study, its implications, and recommendations for future research.

II. Literature Review

Floating solar photovoltaic (FPV) technology is an innovative solution to overcoming land constraints in traditional solar power generation. This literature review highlights the ecological, technological, and operational aspects of FPV systems, their comparative advantages, and challenges. Research emphasizes that FPV systems have significantly fewer negative environmental effects compared to conventional photovoltaic (PV) systems. Conventional PV projects often result in deforestation, increased bird mortality, soil erosion, runoff, and alterations in microclimate. In contrast, FPV systems are less intrusive during the operational and decommissioning phases, making them more environmentally sustainable for tropical regions [6]. Additionally, FPV installations reduce water evaporation and may improve water quality, but their long-term impacts on aquatic ecosystems require further study [7]. The integration of FPV with other renewable technologies, such as hydropower, wave energy converters, and hydrogen production systems, demonstrates significant synergistic benefits. Among these, hybrid FPV-hydropower systems have shown the strongest potential for efficient power generation. Pilot studies and innovations are necessary to enhance the scalability and cost-effectiveness of such hybrid systems, paving the way for global adoption [10]. Performance studies comparing land-based, floating, and submerged PV installations reveal that submerged systems achieve the highest energy efficiency, followed by FPV, and finally land-based systems. FPV systems operate at lower average temperatures (10–20°C cooler), which enhances energy output by 2–10%, depending on the panel type. Innovations such as foam-based floating racking systems have reduced costs to $0.37–$0.61/W, making FPV an increasingly economical option [9][11]. FPV installations have the potential to meet significant energy demands. For instance, utilizing a small fraction of U.S. reservoir surfaces for FPV installations could generate sufficient electricity for the entire nation. Additionally, coupling FPV with hydroelectric power plants provides alternative strategies for balancing energy production and reservoir management goals, such as flood control and water supply [8].

Despite its advantages, FPV faces several challenges:

- **Occupational Hazards**: Installation and maintenance involve risks such as lightning strikes, hailstorms, typhoons, and electrocution [12].
- **Environmental Concerns**: Seasonal water level fluctuations in reservoirs and their impacts on aquatic ecosystems remain under-researched.

- **Extreme Weather Events**: Incidents such as typhoon-induced damage in Japan and fires caused by strong winds in France highlight the need for robust designs [13][14].
- **Regional Challenges**: Remote locations, harsh weather conditions, and grid integration issues hinder FPV adoption in regions like Australia and Brazil.

The comparative analysis of ground-mounted and floating PV systems is exemplified by projects in India, such as the 5 MW and 10 MW FPV installations at SCCL Jaipur, Telangana. These projects showcase the technical and operational efficiencies of FPV over traditional setups.

Typical Ground Mounted PV and Solar Floating PV Plants shown in below.

Figure 2: Ground-Mounted PV Plant at JNTUH, Sultanpur, Telangana.

Figure 3: 5 MW Solar Floating PV Plant at SCCL, Jaipur, Telangana.

Figure 4: 10 MW Ground-Mounted PV Plant at SCCL, Jaipur, Telangana.

Floating PV systems provide an innovative and eco-friendly alternative to ground-mounted PV installations, with benefits including enhanced energy efficiency, reduced land use, and environmental conservation. However, addressing challenges related to installation, maintenance, and environmental impacts is critical to realizing the full potential of FPV systems globally.

III. Materials And Methods

This section outlines the materials, tools, and procedures used in the research on floating solar photovoltaic (PV) systems and their comparison with ground-mounted PV systems. The study primarily focuses on secondary data analysis, drawing from industry reports, academic papers, and policy frameworks, in addition to a comprehensive search for relevant literature. The methodology followed ensures clarity, consistency, and replicability of the research process.

3.1 Materials:

Datasets: The research relied on secondary data sourced from industry reports, academic journals, and policy documents related to floating solar PV and ground-mounted PV systems. Relevant studies, articles, and reports were retrieved through database searches using Scopus, Web of Science, Google Scholar, and the Symbiosis International digital library.

Software and Tools: Microsoft Excel was used for data analysis, particularly for organizing and summarizing the collected data. This tool facilitated the systematic processing and comparison of the information gathered from various sources.

Search Terms: Specific search terms used during the literature review included "floating solar," "Floating PV," "Floating PV module," "floating solar market," "ground-mounted PV," "ground-mounted solar," "photovoltaics," and "solar." These keywords helped ensure a comprehensive search across multiple databases, targeting relevant studies on both types of PV systems.

3.2 Procedure:

Literature Review: The research began with a systematic review of secondary data, focusing on floating solar PV and ground-mounted PV technologies. Targeted keyword searches in databases like Scopus, Web of Science, Google Scholar, and the Symbiosis International digital library identified relevant papers. Additionally, data from government reports, industry analyses, and technical standards were integrated to provide a thorough understanding of the technologies.

Data Extraction: Relevant findings were carefully extracted and categorized according to application, performance, and technological advancements. The extracted information was organized into a comparative framework to distinguish between floating and ground-mounted systems. Key factors such as efficiency, cost, installation, and scalability were considered to ensure a detailed and meaningful comparison.

Analysis: The extracted data was analyzed using descriptive statistics and content analysis techniques. Performance metrics, including efficiency, land usage, installation costs, and environmental benefits, were compared between floating and ground-mounted PV systems. The analysis focused on the technical components of each system, such as inverters, transformers, cable networks, and mooring systems, to evaluate the advantages of floating solar PV systems over traditional ground-mounted systems.

IV. Results And Discussions

Data Presentation:

Floating solar systems present several advantages over traditional land-based solar energy installations. The following are key findings and data related to the adoption of floating solar systems.

Land Requirement:

Challenge: Land-based solar systems face significant space limitations due to high costs or limited availability, particularly in densely populated regions.

Solution: Floating solar systems mitigate these challenges by utilizing water bodies for installations, thus preserving land for other purposes.

Example: A 150 MW floating PV system in Anhui Province, China, saved approximately 3.2 million square meters of land, demonstrating the efficiency of floating solar in minimizing land use.

Data: By utilizing water surfaces, this technology also reduces habitat disruption caused by ground-mounted solar installations.

Enhanced Energy Generation:

Cooling Effect: Floating solar systems benefit from the natural cooling effect of water, helping to maintain lower operating temperatures for solar panels. This cooling effect is especially significant when aluminum frames are used, improving energy conversion efficiency.

Reduced Dust Accumulation: Floating systems experience less dust accumulation due to their position on water bodies, enhancing their performance compared to land-based systems that are often affected by dirt and dust.

Data: Floating systems exhibit an energy efficiency increase compared to land-based systems, with reductions in dust accumulation and lower operational temperatures.

Tracking System Implementation:

Tracking Mechanism: Floating solar systems allow for simpler and more cost-effective tracking system installation compared to land-based systems. These tracking systems, which rotate or tilt panels to maximize sunlight capture, lead to substantial efficiency gains.

Performance Data: Studies have shown energy increases of 15% to 25% when tracking systems are employed on floating solar installations.

Water Security:

Evaporation Reduction: Floating solar panels help reduce water evaporation from water bodies, which is particularly important in water-scarce regions.

Example: Countries in the MENA region are adopting floating PV technology not only for energy generation but also to conserve water by reducing evaporation rates exacerbated by climate change.

Results Summary:

Floating solar systems offer several advantages over traditional ground-based systems:

Land Use: Reduced land requirement by utilizing water bodies.

Energy Efficiency: Enhanced energy generation due to cooling effects and reduced dust accumulation.

Tracking System Benefits: Increased energy production by employing cost-effective tracking systems.

Water Conservation: Reduced evaporation from water bodies in water-scarce regions.

Discussion:

The adoption of floating solar systems presents notable improvements over land-based systems, particularly in land use, energy generation efficiency, and water conservation. These findings align with existing literature that highlights the cooling benefits of water and the potential for reduced dust accumulation in floating systems.

Significance of Findings: The results of improved energy efficiency and land-saving potential are significant, especially for countries or regions with limited land availability and growing energy demands. These findings not only address the challenges of land use but also contribute to the global goal of increasing renewable energy production.

Comparison with Existing Research: The performance of floating solar systems corroborates findings from studies by Rai et al., Choi et al., and Cazzaniga et al., which emphasize the superior energy generation of floating systems due to cooling effects and the ability to incorporate tracking mechanisms.

Performance Comparison:

Authors	Floating PV Output (kWh)	Ground-Based PV Output (kWh)	Efficiency Increase/Comparison
Rai et al. [36]	1892	1600	18.25% increase in energy output
Choi et al. [20]	-	-	10% more efficient (100 kW floating vs 1 MW land-based)
Cazzaniga et al. and Azmi et al. [37]	-	-	4.38% increase at lower radiation, 14.6% at higher radiation levels

These studies reinforce the findings that floating solar systems can outperform traditional land-based solar systems in terms of energy generation, largely due to the cooling effects and better optimization for panel placement and tracking.

Limitations:

While floating solar technology shows promise, there are certain limitations:

Environmental Impact: Large-scale floating solar installations can affect local ecosystems, particularly aquatic life, due to reduced sunlight penetration and changes in water quality.

Data Availability: Comprehensive data on the long-term effects of floating solar systems on water bodies is still limited, and further research is needed to fully understand the ecological and social impacts of these installations.

Site-Specific Considerations: The environmental impacts of floating solar systems vary depending on the water body's location and usage, necessitating thorough environmental assessments before installation.

Future Recommendations:

Ecological Studies: Future research should focus on the long-term environmental impact of floating solar installations, including changes in water quality and local ecosystems.

Improved Tracking Mechanisms: Further developments in cost-effective and efficient tracking systems will enhance the overall performance of floating solar systems.

Expansion of Data: More comprehensive data on energy generation across different regions and climates is necessary to fully evaluate the potential of floating solar systems in various environmental contexts.

V. Conclusions

Reiteration of the Objective:

This study aimed to evaluate the potential of floating solar panels as a viable alternative to traditional ground-mounted solar systems, considering various factors such as power generation, environmental impact, and social implications. The findings highlight the advantages and challenges of both technologies, providing valuable insights into their respective applications.

Key Findings and Contributions:

The research reveals that floating solar panels can generate comparable amounts of power to ground-mounted systems, with the added benefit of being suitable for areas where land availability is limited. Floating PV systems also offer environmental advantages, such as reducing water evaporation and improving water quality by shading the water bodies they are placed on. These systems can alleviate the environmental concerns associated with ground-mounted installations, such as land occupation and disruption of agricultural areas or wildlife habitats. Additionally, the social impacts of floating solar PV farms, particularly on local communities, were explored. While there may be concerns regarding reduced fishing areas, the introduction of these systems can stimulate local economies through job creation and provide opportunities for training programs. The research also underscores the market potential of floating solar technology, which is expected to experience significant growth as costs decrease and demand for renewable energy increases.

Broader Implications:

The findings have broad implications for the future of renewable energy, particularly in regions with limited land availability. Floating solar technology offers a solution for increasing solar energy capacity while reducing land usage, making it a promising option for both urban and rural areas. The environmental benefits, including water management and land conservation, could enhance the sustainability of energy systems globally. Moreover, the study emphasizes the importance of comprehensive environmental assessments before implementing floating solar systems to ensure minimal ecosystem disruption.

The results also suggest that floating solar technology, despite its current high costs and challenges related to installation and maintenance, has the potential to become a significant player in the renewable energy market. As the technology matures and costs continue to fall, it could provide a sustainable and scalable energy source for regions with limited land space.

Recommendations for Future Research:

Future research should focus on addressing the technological and environmental challenges associated with floating solar systems, particularly regarding the durability and long-term maintenance of these installations in harsh aquatic environments. Investigating the development of innovative materials and design improvements could lead to more cost-effective and resilient systems.

Additionally, studies exploring the social and economic impacts of floating solar projects on local communities are essential to better understand how these installations can be integrated into diverse regions. Future research could also examine the combined potential of floating solar with other renewable energy sources, such as wind or hydroelectric power, to create hybrid systems that offer greater efficiency and stability.

In conclusion, as floating solar technology continues to evolve, it has the potential to play a significant role in meeting global energy needs. Future studies should explore its broader applications and practical solutions for overcoming current challenges, paving the way for a more sustainable and energy-efficient future.

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